Thermal Stability Anal ysis for a Heliocentric Gravitational Radiation Detection Mission

W. M. Folkner, P. McElroy, R. Miyake
Jet Propulsion Laboratory, Pasadena, CA

P. L. Bender and R. T. Stebbins
Joint Institute for Laboratory Astrophysics, Boulder, CO

W. Supper
European Space Research and Technolog y Center, Noordwijk, the Netherlands

The Laser infer-cromcfer Space A ntenna (LISA) mission is designed for detailed st udies of lozu-frequency gravitational radiation. The mission is currently a candidate for ESA's post - Horizon 2000 program. Thermal noise affects the measurement in at least two ways, Thermal variation of the length of the op tical cavity to which the lasers are stabilized in troduces phase variat ions in f he interferometer sign al, wh ich have t o be correct ed for by using dat a from the two arms separately. Variations in the dimensions of the spacecraft structure will change the gravitational field experienced by the test masses and the lengt h of f he t ran smif/receive telescope. We have cons tructed a model of an early version of the LISA spacecraft in order to est imate f he thermal variations.

The LISA mission concept currently consists of four spacecraft in 1 AU orbits about the sun -2,0 degrees behind the Earth. A test mass inside each spacecraft is shielded from external non-gravitational influences. The separation between test masses is measured using laser interferometers. The LISA mission goal is to measure gravitational radiation in the range from 10^{-4} Hz to 10^{-2} Hz with greatest sensitivity of $10^{-21}/\sqrt{\mathrm{Hz}}$ between 10^{-3} and 10^{-2} Hz. With twice the arm length being 10^{10} m this means the relative displacement of the proof masses must be measured with an accuracy of 10pm $/\sqrt{\mathrm{Hz}}$. TWCJ spacecraft arc c1osc together (about 200 km apart) and form the vertex of the "V" formation. The two end spacecraft define the size of the array, The individual orbits arc chosen to maintain the formation as exactly as possible.

The master laser cm one of the central spacecraft is locked to a reference cavity. A change of length of the cavity due to temperature change produces a laser frequency shift and a corresponding error in the displacement measurement of the test mass, The laser phase noise can be canceled between the arms using a Fourier-transform processing technique by an amount $4\pi f\sigma_l / c$ where σ_l is the uncertainty in knowledge of the arm lengths and f is the observation frequency. The thermal noise sets the level of arm length determination needed and also the precision needed in the phase measurement to allow the necessary level of phase noise cancellation.

A cross-section of the payload module within each spacecraft is shown in Fig. 1, The payload module includes a structural graphite-epoxy cylinder within which arc the test mass, telescope, and position measurement laser and electronics. The laser is mounted on a radiator disk at the one end of the graphite-epoxy cylinder. Capacitive sensors arc used to measure the position of the test mass within a central optical bench which is rigidly attached to the spacecraft. The displacement measurements are used to center the spacecraft about the test mass. Electronics for the capacitive sensors and amplifiers for the laser photo-diodes arc mounted on a disk between the optical bench and the laser radiator. A cylindrical thermal shield surrounds the payload structural cylinder to provide isolation from the rest of the spacecraft. The external spacecraft is shown in Fig. 2. It consists of a central structural cylinder within which the payload is suspended, and a trapezoidal box which contains the attitude control thrusters and electronics, the telemetry system, star trackers, and other elements. Solar panels located on the sun-facing side of t he box provide spacecraft power. The normal to the "top" of the box always points 30° from the sun.

A thermal model for the entire spacecraft was formed with single nodes for the box panels, solar panels, optical bench, telescope, laser radiator and electronics disk, The largest thermal load is from incident sunlight. Electrical power dissipation occurs on the outer spacecraft panels; the laser radiator, the payload electronics disk. A small amount of power is needed on the optical bench to bias the photodetectors and drive a phase-modulator. Observed solar insolation variations from 10^{-4} Hz to 10-2 can be described by a power spectral density of $\Delta L = 1.3\times 10^{-4} f^{-1/3} L_0$ W/m²/√Hz with L = 1350 W/m². The power fluctuations of electrical components will be actively controlled to keep them from inducing temperature variations greater than those caused by solar variation.

The transfer functions giving the temperature response for unit variation in power dissipation for the optical bench (which contains the laser reference cavity) are given in Table 1. As an example of reading Table 1, the variation of solar insolation of 1.8 W/m²/√Hz at 10^{-3} Hz is multiplied by 3.7×10^{-9} to find the optical bench temperature noise of 6.7 nK/√Hz. To keep the electronic power variations from producing thermal noise in excess of this, the power dissipation of the payload electronics will have to be controlled to 10^{-4} W/√Hz and the photo-diode power will have to be controlled to 0.3 μW/√Hz. The photodiodes (and phase modulator) are assumed to draw 0.4 W at 40 V. A 200 Ohm resistor (small compared to the load resistance of 4000 Ohm) is placed in series with the load. The voltage across the load and across the 200 Ohm resistor are measured with an op-amp with voltage noise at 1 mHz of 1 μV/√Hz. **The voltage and power measurement are multiplied to give the power dissipation and included in a feedback loop that maintains constant power.** The power noise at 1 mHz is then 1 μV/√Hz x 0.01 A + 5 nA/√Hz x 40 V = 0.2 μW/√Hz.

The primary payload masses, aside from the optical bench, are the telescope, the payload electronics, and the laser/radiator combination with masses 13.97 kg, 3.53 kg, and 14.85 kg. The distances to the test mass are -0,355 m, 0.250 m, and 0.522 m. The nominal acceleration of the test mass due to the other payload masses is 2×10^{-12} m/s² and the acceleration gradient is **$8{,}6\times10^{-8}$/s². The three** masses move with respect to the test mass due to thermal expansion of the payload cylinder from which they are suspended, **which has coefficient** of **thermal expansion 0.4×10^{-6}**/K. Table 2 gives **the position noise from thermally-induced gravitational changes** driven **by** solar **variations.**

Table 1. Temperature response of optical bench for unit change in power dissipation.

f(Hz)	solar variation K/(W/m²)	spacecraft electronics K / W	payload electronics K/W	Laser K/W	Photo-diodes K/W
1.0E-06	5.9E-01	3.1E-01	3.3E+00	3.7E-01	8.7E+00
1.0E-05	1.6E-03	1.3E-03	1.9E-01	3.1E-03	1.2E+00
1.0E-04	3.5E-06	4.6E-07	2.1E-03	5.4E-06	1.2E-01
1.0E-03	3.7E-09	3.2E-11	2.1 E-05	5.4E-09	1.2E-02
1.0E-02	3.7E-12	3.0E-15	2.1E-07	5.4E-12	1.2E-03

Table 2. Thermally-driven gravity change

f(Hz)	motion noise (m/√Hz)
1.0E-06	2.8E-05
1.0E-05	2.2E-08
1.0E-04	8.2E-12
1.0E-03	2.4E-16
1.0E-02	7.6E-21

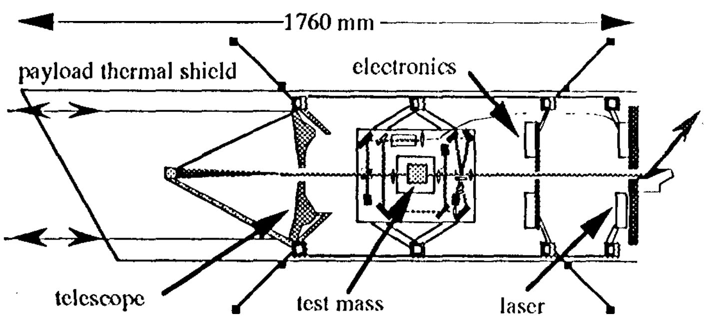

Figure 1, LISA payload schematic

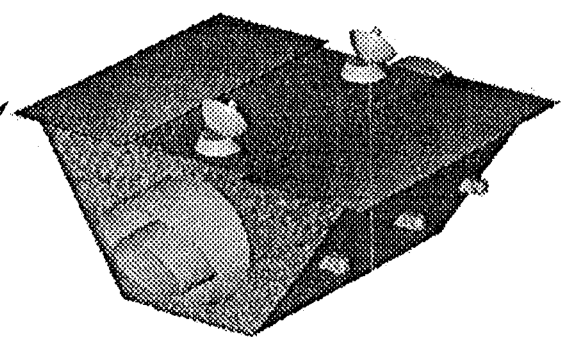

Figure 2. LISA spacecraft

1. M. Woodard, Short-Period Oscillations in the Total Solar Irradiance, Thesis, U. Calif. San Diego, (1984)

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